A Life Cycle Thinking Approach Applied to Novel Micromobility Vehicle

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ABSTRACT

While the production of cars has high environmental costs, producing and maintaining micromobility vehicles might consume fewer resources. Likewise, replacing the car with active mobility transportation modes reduces noise and air pollution. The Life Cycle Assessment (LCA) methodology contributes to study such environmentally sustainable solutions. We present a "cradle-to-grave" analysis by tracking the activity from the extraction of raw materials until the product's life ends. The goal is to carry out an LCA of a novel micromobility vehicle under a life cycle thinking perspective. The LCA tool - Good to Go? Assessing the Environmental Performance of New Mobility, developed by the International Transport Forum - was used to model the baseline and alternative scenarios. The vehicle's materials, primary energy sources for battery charging, use of the vehicle as a shared mobility mode, among other factors, were changed to assess the energy use and greenhouse gases (GHG) emissions during the entire life cycle chain. The LCA results at the baseline scenario for the micromobility device, the Ghisallo vehicle, are similar to the values of other micromobility vehicles. Energy consumption (Mega Joule [MJ]) and GHG emissions (grams of equivalent CO_2) per vehicle-kilometer are 0.36 [MJ/v-km] and 29 [g CO_2 eq/v-km], respectively. For this personal mobility vehicle, it is a conclusion that most GHG emissions are due to production (42% of the total). Air transport from production to sales site increases the impact by 10%. Finally, we present measures to decrease the energy and GHG emissions impact of a micromobility device life cycle.

Keywords: Life cycle assessment; Micromobility; Mobility; Sustainability; Greenhouse Gas emissions.

1. INTRODUCTION

The world has been facing considerable populational growth rates, including an agglomeration in cities. Nowadays, more than 50% of the global population lives in cities, and by 2050 the rate of people living in urban places is expected to reach more than 70%. This development boosts the growth in demand for resources, basic infrastructures, and public services, multiplying the number, size, and complexity of challenges to face and potentially bringing social differences (1). Hence, cities face severe mobility-related issues due to the fast rise of motorized vehicles, with traffic congestion, air pollution, and greenhouse gas emissions (GHG) at the head of the problem (2–4). Especially in urban areas where air and noise pollution, energy consumption, and CO2 emissions are partly related to transportation. By 2018, 71% of the GHG emissions coming from the transportation sector were due to road transportation. In other words, road transportation contributes to more than 22% of the total GHG emissions and more than 27% of the world's final energy consumption (5–8). So, cities deal with adverse externalities of car travel and society understands the negative impacts of such issues, particularly for their wellbeing (9).

Although the internal combustion engine vehicles production has several environmental costs - LCA estimations of 200 gCO_{2eq}/km for 105,000 kilometers (10) - the production and maintenance of micromobility vehicles requires fewer resources. For example, an e-scooter was estimated to produce 202 gCO_{2eq}/passenger-mile. Another one was estimated to have a global warming impact of 165 gCO_{2eq}/km for lifetime covered distances of 2,117 kilometers over just six months (11,12). Additionally, active modes like bicycles, e-scooters, and others reduce air and noise pollution in the road transport sector.

Lately, an enormous increase of these vehicles operating in cities has been verified. These are typically bicycles, scooters, mopeds, and others. They comply with the norm that characterizes micromobility vehicles, which means vehicles weigh less than 227 kg. Their average speed is below 48 km/h (13). For example, from 2017 to the moment, E-scooters have invaded more than 100 cities worldwide (14). Also, shared mobility systems for bicycles raised from covering just ten cities by the 1990s to more than 2900 places nowadays (15–17). So, micromobility is exponentially being adopted. It is changing the way people move in cities, given its potential to help cities reduce harmful emissions (18–20). It has emerged in the urban context given the potential to satisfy first/last mile trips. So, new mobility options, systems, services, and patterns related to shared mobility made the coexistence of active modes in the urban transport sector more significant (20).

However, the assessment of sustainable integration of innovative solutions requires precise concepts and methodologies of analysis that may include resources consumption and economic, social, health, and environmental indicators (8,21). In their efforts, scientists and engineers often focus their attention on just a single stage of a system's use. However, it is only by adopting a cradle-to-grave methodology of life cycle assessment that a global picture of a products' impact on the environment can be seen (22,23). Additionally, micromobility vehicles' life-cycle impacts on energy demand and greenhouse gas emissions are often unknown (24). Research also suggests adopting a flexible and iterative life cycle approach to achieve the full potential of sustainable integration of micromobility (25).

The paper aims to produce a life cycle assessment of a novel micromobility device using the methodology of assessing the environmental impact of the product's lifetime. In other words, from the materials' extraction (cradle) to its production and use until its final use (grave). By final use, it is considered the last time that someone travels using this vehicle. Later, comparisons between the novel vehicle and existent micromobility vehicles are performed to validate obtained results. The life cycle assessment will be modeled following the methodology 'ITF Good to Go? Assessing the Environmental Performance of New Mobility', by Pierpaolo Cazzola and Philippe Crist at International Transport Forum. It is applied using a dedicated tool, the excel tool developed under this methodology (24). The vehicle, a tricycle, was developed in the scope of the Ghisallo project, and it allows the user smooth driving with comfort, stability, safety, and low effort. At the same time, the developed group with steering, suspension, and the frame allows easy adaptation to transport in public modes like trains and buses, as seen in **FIGURE 1**. For simplification, we refer to the novel micromobility vehicle as the Ghisallo vehicle for the remainder of the manuscript.

FIGURE 1 - Prototype of micromobility vehicle developed at Ghisallo project

The paper organization is as follows. Section two discusses the literature review on topics related to the life cycle assessment studies done so far around mobility and micromobility. Section three is devoted to presenting the methodology for life cycle assessment Good to go? Assessing the Environmental Performance of New Mobility. The obtained results and a critical overview are presented in section four. Finally, section five presents concluding remarks.

2. LITERATURE REVIEW

Life cycle thinking (LCT) is an approach applicable to economic, social, and environmental issues, supported by multiple methodologies. Life cycle assessment (LCA) is the one used for obtaining environmental indicators since it assesses the environmental flows involved in a product or service's entire life cycle. Primarily by calculating their contribution to different areas such as climate change, primary energy use, or human health impacts. Due to its holistic approach, LCA can enlighten trade-offs between different impact categories and different stages of the life cycle. LCA identifies and quantifies the extraction and consumption of resources in various stages and the spread of emissions to the air, soil, and water (26).

LCA studies on mobility and micromobility from previous literature have been documented in the last 15 years. In 2014, bicycles from the brand Specialized were studied to evaluate and quantify their sustainability rate. The authors concluded that better communication between players on the whole supply chain was needed to enhance the life-cycle environmental impacts (27). Other authors stated that infrastructure's impact should be included in LCA studies. At once, some studies reveal that a conventional bicycle would be less harmful than electric ones, electric or diesel cars, and scooters. However, these do not reveal if their production stage could be more efficient (28,29). Also, comparisons between walking, bicycling, or electric-bicycling modes against other public transport modes like buses were performed under Carnegie-Mellon's EIO-LCA methodology. It was concluded that electric bicycles consume less than 10% of the needed energy to power a sedan while emitting 90% fewer GHGs per passenger-kilometer than a bus off-peak (30). Cherry et al. have even studied the environmental impacts of producing two-wheelers with different materials and manufacturing processes. Their comparisons show that motorcycles and cars emit several times more pollution per kilometer than bicycles. Furthermore, they advise considering the energy mix of the regions from where the energy comes to power batteries. The batteries themselves could be Li-ion since lead-acid ones are not needed for electric bikes, but the life cycle cost is still a concern (31). When quantifying the LCA of different battery types, Liu et al. later confirmed that prolonging the batteries' lifetime and raising the recycling rates will decrease the environmental impacts. Also, it was identified that producing energy from cleaner sources than the coal was necessary. Especially if later it is stored on batteries like it is already done for some electrical bikes in China (32).

Interest has grown around the concept of shared mobility, especially with micromobility vehicles. The same is true for the researchers' interest in complete LCA studies of these devices when including factors like their shareability. It is critical to conclude if it benefits the final impacts regarding sustainability. A study done in Paris with bicycles, e-scooters, and e-mopeds concluded that multiple scenarios and cities should be considered to estimate the environmental performance of micromobility devices (28). Moreover, due to the lower expected lifetime of shared devices, the LCA analysis rated individual ownership of micromobility devices as more efficient than shared. However, there are reported suggestions that future studies should consider the effects of cumulated mileage, maintenance, and transportation of the vehicles from the production site to the cities (28). Semih Severengiz et al. included other factors in their LCA to e-scooters at Bochum, Germany, like air quality, public space demand, and global warming potential. They conclude that for a better overview, it is crucial to understand the behavior of the users of new multi-modal transportation systems. It is suggested that to improve the results of LCA studies, the inclusion of energy demand, noise pollution, and battery change station's inherent impacts will be vital (7).

Following the interest for LCA on shared micromobility, Gu et al. conclude that based on surveys, the use of shared bicycles is more prevalent among young and low-income people. It is attractive to replace walking and public transportation, so 25-45-year-old people would benefit from the environmental impacts of shared-micromobility. It brings higher carbon cost savings since it replaces more pollutant trips. Likewise, raising the booking cost would benefit the economic health if bicycles' lifetime were longer than two years to guarantee environmental sustainability. The LCA results suggested that reducing the volume of shared bicycles per user and replacing materials like aluminum with steel would benefit the rates of CO_2 emissions (33). Mao et al., on their own, assessed the life cycle of shared bicycles in China to estimate the environmental impacts at all stages of life. Results showed that a mean value of 81% of environmental impact was due to the production stage, which shows that the usage phase and recycling stage are not that harmful. Here, aluminum and rubber were pointed as the materials that contributed to around 80% of the environmental impacts calculated on their LCA methodology at the manufacturing stage.

Shared mobility using bicycles has four identified areas of improvement on its environmental performance, which are 1) to optimize its distribution and to re-rout or reposition bicycles on a more sustainable approach for the cities; 2) to encourage private car users to switch to shared bicycle use; 3) to extend life expectancy to reduce environmental impacts and 4) to increase cycling efficiency to improve the environmental performance of dock-less systems (3).

As the complexity of last-mile trips increases, it needs to be tackled with simpler vehicles, so the tricycle is a possible solution. This vehicle is considered a micromobility vehicle if complying with normative parameters. In the city of Rio de Janeiro, its efficacy was previously evaluated through LCA. Tricycles were considered part of a zero-emission strategy to replace combustion vehicles with electrically powered ones. From an LCA point of view, only electrical power production was considered to be potentially harmful if fossil fuels were used. In any case, the cargo delivery of goods and services by using tricycles was concluded from an LCA to reduce equivalent CO_2 emissions by 23,37 kg (34).

Although the literature presents independent studies on several micromobility vehicles and shared mobility, many identify the need to include more socioeconomic or health indicators to improve LCA. Also, every time a new product arises in the market, an LCA is recommended, especially if some want to confirm its collaboration with the identified potential of the micromobility concept in its three pillars: 1) to reduce GHG emissions by replacing combustion vehicles, 2) to increase reliability with sustainable associated business models, and 3) to reduce obstacles of mobility in cities (35).

In **TABLE 1**, we summarize the literature review, highlighting the goal and LCA method of each of the key cited studies and their significant conclusions and limitations.

TABLE 1 - Summary of Literature Review

(Ref) year	Goal and method	Conclusions and limitations
(30) **2010**	Study aims to quantify energy consumption and environmental impacts of walking, (e)bikes, and others using LCA methodology – Carnegie-Mellon's EIO-LCA.	People's habits and economic factors influence how transport is used. Individual behaviors are essential for a specific LCA.
(27) **2014**	Performs a quantitative analysis of manufacturing sustainability of Specialized bicycles and a qualitative evaluation of the current interest in sustainable bicycles.	Besides the promising LCA results, media messages restrict the users' opinion to believe (e-)bicycles are not sustainable enough, lowering the customers' desire for more sustainable ones. Industries and governments should be more involved.
(36) **2019**	LCA study – Monte Carlo analysis to quantify the environmental impacts of e-scooters such	Lifespan is a highly sensitive factor for e-scooters. Global warming potential (GWP) is mainly due to their production

	as global warming, acidification, eutrophication, respiratory effects.	and combustion vehicles' use for operational services. GWP will decrease if the lifetime of shared e-scooters increases.
(33) **2019**	LCA model with Gabi software based on results from a survey to identify changes in modes of transport after introducing shared bicycles in a given city.	The industry should opt for eco-friendly materials in shared bicycles. The lifetime of the shared bicycle must be more than two years to ensure the environmental compatibility of this emerging "sustainable" transport mode.
(7) **2020**	LCA of shared e-scooters in Bochum, Germany, quantifies environmental and social indicators like Global Warming Potential, local air quality, and public space demand.	New mobility services can reduce the environmental impact of urban areas as a transport system. Understanding the user behavior on new mobility services is crucial, and relevant data should be collected.
(37) **2020**	LCA on shared e-scooters for the city of Berlin with operating scenarios modeled to evaluate alternative ones against the base one.	The GWP of shared e-scooters is mainly caused by the production stage, particularly aluminum parts. Their lifetime, the required distances to collect lost/damaged batteries/e-scooters, the vehicle type for that effect, and the electricity sources are vital indicators.
(28) **2021**	Modal Integrated Life Cycle Assessment of shared micromobility services versus private alternatives, based on field data.	Maintenance is vital for shared e-scooters. Air transporting vehicles (planes) affects the LCA results. Unless it has low carbon intensity, the electricity supply mix jeopardizes the labeling of e-scooters as "green". Shift from aluminum to steel on bike frames is suggested.
(38) **2021**	A life-cycle assessment of the bicycle sharing service in China to estimate impacts at all stages of the life-cycle, with nine categories of environmental impact.	The production stage contributes to 81.18% of the ecological impact. As harmful items, aluminum precedes rubber. Production and preservation enhancement, materials choice for longer device/service life, and frame design for easier care are emerging R&D topics.

Thus, since Ghisallo vehicle will be a new product arising in the market, an LCA is recommended. We present a holistic approach that combines a life cycle assessment of the Ghisallo vehicle in this work, where part of the innovation is also related to the device's design.

3. METHODOLOGY

This section describes the life cycle assessment approach, the characterization of the vehicle with inventory phase, and the definition of goals and scope of this life cycle thinking work. This methodology allows the identification of the leading environmental impacts of the Ghisallo project prototype. **FIGURE 2** shows an overview of the methodology.

FIGURE 2 - Overview of the methodology steps

The present life cycle assessment was performed with a cradle to grave approach from raw materials acquisition to the vehicle's end-of-life of Ghisallo vehicle. The software tool used to perform the LCA was the Good to Go? Assessing the Environmental Performance of New Mobility by International Transport Forum, ahead mentioned ITF-Good to Go (24). This tool assesses the environmental impacts of several transport modes based on their technical, operational, and maintenance characteristics.

Such a tool considers three critical components of life cycle assessment used in the transport sector to evaluate the energy demand and environmental impacts associated with a given mobility mode. Those are the vehicle, the fuel (energy), and the infrastructure. Therefore, this platform allows evaluation of six different types of results which are: energy consumption per kilometer [MJ/km], energy consumption per passenger and kilometer [MJ/p-km], energy consumption per vehicle and kilometer [MJ/v-km], GHG emissions per passenger and kilometer [g CO_2 eq/p-km], GHG emissions per vehicle and kilometer [g CO_2 eq/v-km], and GHG emissions per vehicle [g CO_2 eq/v]. However, since Ghisallo is for only one passenger, this list is reduced to four results indicators, and the functional unit considered was vehicle-kilometer (v-km).

3.1 Goals and Scope definition

The definition of the scope of the analysis using this tool was crucial to guarantee the study's boundaries. So, the scope of this work is the Ghisallo vehicle, a tricycle with an electric motor and lithium battery which the Portuguese National Energy Grid powers. This vehicle is produced in Vila Nova de Gaia, Portugal. Its distribution in the whole continental territory was considered to be executed by trucks from the production site to the sales site. The vehicle usage was considered as only for one passenger and with a mean mileage of seven kilometers and an expected lifetime of ten years. It was considered that during this period, the battery and tires would be replaced once.

The LCA to perform can be divided into five pillars: the production, transport, infrastructures, energy, and operational services (shared mobility) associated with this vehicle. For each step, input parameters were considered knowing that each process depends on energy and resources/materials demand, resulting in energy consumption and GHG emissions as outputs. Therefore, the boundaries of analysis were defined based on a framework inspired by the one from **FIGURE 3** (39), which resulted in a base scenario that can be schematically represented by **FIGURE 4.**

FIGURE 3 - Transport infrastructure life stages (39)

FIGURE 4 - Framework of the life cycle assessment

3.2 Life Cycle Inventory (LCI)

The Life cycle inventory (LCI) of the vehicle production and end-of-life phase was modeled considering the previously developed work regarding the existing prototype of the Ghisallo vehicle, namely the bill of materials, the technical draw, and the assembly drawing with CAD. Using the ITF-Good to Go? tool, a similar vehicle to the case study was selected for later edition of all parameters, knowing that multiple inventory data come from GREET (Greenhouse Gases, Regulated Emissions, and Energy use in transportation) (40), which functions as an LCA database. GREET is divided into two modules where GREET1 assesses energy use regarding well-to-wheel and fuel systems' emissions, while GREET2 assesses energy use and emissions of the vehicle's manufacturing cycle, considering primary energy use (oil, natural gas, coal), GHG emissions (like CO_2, N_2O, and CH_4), and atmospheric pollutants (like Sox, NOx, VOC, PM10, PM2) (40). The inventory was therefore complemented with information from GREET2 as other input data.

According to the five pillars of Ghisallos' life cycle assessment (**FIGURE 4**), the baseline scenario inventory and inputs to the system were therefore defined as explained in the following sections (without considering operational services due to shared mobility):

3.2.1 Production

For the pillar of production of our vehicle, it was considered that its expected lifetime would be ten years with a mean daily mileage of 7 km/day. It is a vehicle of just one passenger with a 0.7 value of utilization factor (that considers vandalism, theft, accident, and vehicle non-use days). Therefore, Ghisallo is finally expected to travel approximately 2,600 km/year, which means 18,200 km/vehicle in its actual lifetime, which is seven years when affected by the utilization factor. It was also considered that each tire and the battery would be changed once in a lifetime. Thus, we included three spare units of tires and one battery in the bill of materials. The electric motor weighs 2.79 kg (Motor Shimano E7000), while its composition is 36% steel, 28% copper, and 36% cast aluminum (41). In **TABLE *2***, we summarize more information on the characteristics of Ghisallo vehicle, a micromobility device, mainly its materials, energetical and environmental information regarding the production of parts, including spare parts on the count of vehicles' pieces. Moreover, Ghisallo is a vehicle that includes other pieces like (cork handles, nylon washers, saddle, and electrical circuit board) which were considered as "Others" in the table.

TABLE 2 – List of parts of the Ghisallo vehicle, total weight per type of material, the energy needed to produce it, and respective GHG emissions.

Material	Nº of pieces	Weight per material [kg]	%Mass per material *	Energy needed per kilogram (recycled) [MJ/kg]	GHG emissions (recycled) [g CO_2 eq/kg]
Steel	186	12.85	46.46 %	31.3 (19.1)	2,844 (1,287)
Stainless steel	1	0.43	1.45 %	26.1	1,772
Extruded Aluminum	28	4.61	15.46 %	121.0 (24.3)	7,361 (1,525)
Cast Aluminum	6	0.61	5.42 %	134.4 (27.8)	8,174 (1,742)
Copper/Brass	13	0.97	5.85 %	40.3	2,797
Plastic	17	2.75	9.20 %	89,1	4,064
Rubber	12	4.01	13.44 %	49.9	3,575
Others	10	0.81	2.72 %	140	9,000
Total	273	27.04	100 %	---	----

*Note: the percentage of mass per material (column4) includes the mass of the electric motor, which is an extra piece of the Ghisallo with around 1 kg of steel, 0.781 kg of copper, and 1kg of cast aluminum and considers the percentage of recycled material per piece. Columns nº 5 and 6 include values to consider the cases when the steel, extruded aluminum, or cast aluminum pieces were manufactured after the recycling process.

So, for the execution of the life cycle assessment, the vehicle's total weight without a battery was considered to be 29.83 kg. According to the information from GREET2, it was also considered that 26% of the steel, 11% of extruded aluminum, and 85% of cast aluminum are recycled materials, the reason why we considered the energy needed and GHG emissions for these specific recycled materials. The Ghisallo vehicle also includes a battery with a specific energy of 0.149 [kW/kg].

By considering the database of values of GREET2, we could finally calculate the values of energy consumption and GHG emissions during the production, assembly, and dismantling/end of life of vehicle and battery. The final values are summarized on **TABLE *3***.

TABLE 3 – Summary of energy consumption and GHG emissions at the production stage of vehicle and battery, including assembly and dismantling phases

Value/Product		Vehicle	Battery
Energy consumption [MJ/product]	**Production**	1,608.96	1,127.44
	Assembly	245.32	259.46
	Dismantling	67.58	18.22
	TOTAL	1,921.86	1,405.12
GHG emissions [g CO_2 eq/product]	**Production**	107,504.62	72,121.54
	Assembly	16,066.25	16,625.17
	Dismantling	4,574.19	1,233.23
	TOTAL	128,145.06	89,979.94

The values from the table include spare parts, therefore totaling 3,326.98 [MJ/ghisallo] and 218,125.00 [g CO_2 eq/ghisallo] when considering vehicle plus batteries. Finally, the inventory considers a value of 0.058 [MJ/vehicle] and 4,367 [g CO_2 eq/vehicle] due to fluids operating.

3.2.2 Transport

Regarding the transportation of the Ghisallo vehicle, this LCA considers that heavy goods transport vehicle powered by diesel travels a mean delivery distance of 205 kilometers with a package of 10 kilograms to perform the transportation between the production site and sales/booking site. Therefore, considering the assumptions of the ITF – Good to Go tool for LCA assessment of these vehicles, the energy consumption of a distribution transport per Ghisallo vehicle is 10.3 [MJ/vehicle] while the GHG emissions are 915.5 [g CO_2 eq/vehicle].

3.2.3 Infrastructure

As for the infrastructure, we approached the baseline case scenario definition by considering that the vehicle will use road (type1) infrastructures all the time, avoiding cycling paths (type2). In any case, both for road or bike lanes, the lifetime of infrastructure was considered to be 30 years knowing that each (type1;type2) of these consists of a mixture [tons/km_{track}] of asphalt (1.00;0.12), cement (212.50;22.5) and steel (0.10;0.00). Therefore, considering the materials' distribution for each type of infrastructure, the quantity of recycled steel used on those, and the usage rate of the vehicle per kilometer of a road or cycling path, we calculated the energy needed to produce each infrastructure type. For type 1 (road), 1,088,379 [MJ/km_{track}] is the energy needed while for infrastructure type 2 (bike lane) 114,999 [MJ/km_{track}] is the value. Similar to what is done on the production pillar, through the ITF tool, we consider GHG emissions per material used on infrastructures to finally achieve the GHG emissions per kilometer of track values of 371,886.01 and 39,355.09 [kg CO_2 eq/km_{track}], respectively. We inevitably converted both types of values to the functional unit by considering the mileage that Ghisallo would run on each type of track per year during its lifetime.

Thus, the values of energy consumption and GHG emissions per vehicle-kilometer from the point of view of infrastructures (type 1 and type 2) were: 0.033 and 0.008 [MJ/v-km]; 11 and 3 [g CO_2 eq/v-km]. As mentioned, for the baseline case scenario, our vehicle uses the road track 100% of the time. Thus, the LCA results do not consider the values of the bike lane.

3.2.4 Electricity

The baseline scenario of LCA considers a fully powering of our vehicle's battery by electrical energy, so considering the mix of energy production at the Portuguese National Energy Grid, characteristics were assigned as presented in **TABLE 4**. From the table, the final value of energy intensity well-to-tank of REN is 0.914. Therefore, once we consider the final mileage of the vehicle after seven years, the energy consumption due to electricity production to power the device was 2,632.95 [MJ/vehicle], and the GHG emissions come to 101,854.73 [g CO_2 eq/vehicle] as the vehicle would consume 0.021 [kW.h/km]. Here we considered both the energy flow from well-to-tank and tank-to-wheel.

TABLE 4 – Mix of energy sources by REN, Portugal in 2020 (42)

Energy source	Energy produced [GW.h]	%Total energy	Energy intensity	GHG emissions [g CO_2 eq/kW.h]
Petroleum	4,624	9.6	3.5	886.9
Natural Gas	11,012	22.9	2.3	425.9
Coal	2,127	4.4	3.0	1000.8
Biofuels	3,286	6.8	4.9	32.2
Water	13,794	28.7	1.1	0.0
Solar	1,269	2.6	1.1	0.0
Wind	12,053	25.0	1.1	0.0

3.3 Alternative Scenarios

After completing the characterization of the baseline scenario, we analyzed the possibility of some changes over the mentioned pillars of analysis, including operational services if Ghisallo was considered as a shared micromobility vehicle.

Therefore, five alternative scenarios were studied, and a 6th one combined the results of the best three regarding energy consumption and GHG emissions. In **FIGURE 5**, the pillars of analysis which suffered changes are summarized.

FIGURE 5 – Summary of alternative scenarios to study based on LCI changes in main pillars

Hence, at the adopted excel sheet, the tool from ITF – Good to Go, some input values were changed for a complete analysis on their relevance over the final results of LCA from a perspective of energy consumption and GHG emissions. At alternative scenario 1, following the literature review, it was considered that 18 aluminum parts of the existing Ghisallo vehicle would be replaced by steel or stainless steel (27,29,36,37). Therefore, in this scenario, the vehicle weight was now 33.8 [kg] while some changes to the columns of "Nº of pieces", "Weight per material [kg]", and "%Mass per material" in **TABLE *2*** had to be considered.

As a result, the inventory table considered at this scenario was according to the one shown at **TABLE *5***.

TABLE 5 - List of parts of the Ghisallo vehicle, total weight per type of material, the energy needed to produce it, and respective GHG emissions for alternative scenario 1

Material	Nº of pieces	Weight per material [kg]	%Mass per material *	Energy needed per kilogram (recycled) [MJ/kg]	GHG emissions (recycled) [g CO_2 eq/kg]
Steel	201	16.44	53.01	31.3 (19.1)	2,844 (1,287)
Stainless steel	4	3.60	11.60	26.1	1,772
Extruded Aluminum	8	1.51	4.88	121.0 (24.3)	7,361 (1,525)
Cast Aluminum	8	0.92	2.97	134.4 (27.8)	8,174 (1,742)
Copper/Brass	13	0.97	3.13	40.3	2,797
Plastic	17	2.75	8.87	89,1	4,064
Rubber	12	4.01	12.93	49.9	3,575
Others	10	0.81	2.61	140	9,000
Total	273	31.01	100%	---	----

*Note: the percentage of mass per material (column4) includes the mass of the electric motor, which is an extra piece of the Ghisallo with around 1 kg of steel, 0.781 kg of copper, and 1kg of cast aluminum and considers the percentage of recycled material per piece. Columns nº 5 and 6 include values to consider the cases when the steel, extruded aluminum, or cast aluminum pieces were manufactured after the recycling process.

In alternative scenario 2, the differences to the baseline scenario were on the transport pillar. The trips between the production and sales site were considered to be performed by plane or truck. This time, the medium-sized truck is considered to cover a distance of 245 kilometers instead of 205 of the base case, while the plane trip was considered to average 1200 kilometers. This scenario is similar to a possibility where the Ghisallo vehicle would be sold at the Portuguese islands, so it would have to move from Vila Nova de Gaia to Madeira or Azores by plane and then perform a few more kilometers on the dedicated van for transportation.

In alternative scenario 3, we inputted to the LCA that 10% of the time, Ghisallo would be traveling on the road (infrastructure – type1) and 90% of the time on the bike lane (infrastructure – type2). Therefore, this time both types of tracks were considered when looking at the values presented in section 3.2.3. This assumption was taken to consider a scenario of a city where bike lanes are well developed. However, a sensitivity analysis should be taken in the future to consider different scenarios of bike lane use.

If Portugal and the world are looking for carbon neutrality by 2050, we also found it of interest to analyze in the alternative scenario nº4 what would be the impacts of the Ghisallo LCA if renewable energy sources entirely powered its battery. So, in this case, we considered that the values from **TABLE 4** would have a distribution where non-renewable sources were responsible for 0% of the energy mix. That is related to the assumption of ITF Good to Go about GHG emissions and Energy intensity of solar panels, wind turbines, and other renewable energy sources related infrastructures being zero. One more time, a broader sensitivity analysis could take place in future studies for one to understand the volatility of the results depending on different grid mixes in different places around the world for the Ghisallo vehicle.

Finally, scenario 5 is the one where the impacts of a shared mobility perspective were analyzed. Given the perspective of modeling the Ghisallo vehicle on a similar approach to an electric scooter, we had to consider changes on the five pillars compared to the baseline scenario. To guarantee an accurate comparison between scenarios, we initially considered the mileage during real life would be the exact 18,200 kilometers with the vehicles traveling 7km/day. Thus, after affecting an extra utilization factor of 0.45 due to vandalism, utilization, and tampering (typical characteristics at shared mobility scenarios), it resulted in an actual mileage per vehicle of 8,334 [km/v] instead of the 18,200 as the actual lifetime of the vehicle would drop from 7 to 3.2 years. Also, we considered that tires would be changed twice instead of once, which means six spare parts of tires (against the previous 3). Once the lifetime, the number of pieces, and mileage per life cycle changed, all the other pillars of infrastructure, transport, and electricity were affected. Also, as the vehicle becomes a shared device, the pillar of operational services had to be considered. That resulted in an extra 8,267.34 [MJ/vehicle] and 572,292.80 [g CO_2 eq/vehicle] due to a van circulating in the city to pick abandoned/damaged Ghisallos or replace them in pick-up stations. Again, extra care has to be accounted for to guarantee homogeneity between the comparisons. This because the crucial values need to be assessed according to the functional unit and the vehicle in the study. Therefore, later in the results, these two values are presented per vehicle and kilometer.

Based on the results, we completed the alternative scenarios by maximizing the efforts to obtain an LCA where environmental impacts are the less impacting on total energy and GHG emissions per vehicle-kilometer. Therefore the 6th scenario includes the changes considered in scenarios 1, 3, and 4 to maximize the benefits.

To summarize, **TABLE 6** presents the main changes that were considered when performing the calculations.

TABLE 6 – Summary of main characteristics for LCA studies in different scenarios.

Parameter	Base Case	AS1	AS2	AS 3	AS 4	AS 5	AS 6
Ghisallo lifetime [km]	18,200	18,200	18,200	18,200	18,200	8,334	18,200
Ghisallo weight [kg]	29.83	33.80	29.83	29.83	29.83	29.83	33.80
Inventory	Original Table 2	Greener Table 5	Original Table 2	Original Table 2	Original Table 2	Original Table 2	Greener Table 5
Transport	Truck	Truck	Truck + Plane	Truck	Truck	Truck	Truck
Lane type	100% Road	100% Road	100% Road	10%Road 90%BL	100% Road	100% Road	10%Road 90%BL
Electricity mix	PGM Table 4	PGM Table 4	PGM Table 4	PGM Table 4	100% Renewables	PGM Table 4	100% Renewables
Operational Services	Non existent	Non existent	Non existent	Non existent	Non existent	Diesel Van	Non existent

*Note: AS means Alternative Scenario; Ghisallo weight includes the motor weight but not the battery 29.83 equals 27.04 + 2.79. 33.8 equals 31.01 + 2.79. BL stands for Bike Lane; PGM stands for Portuguese Grid Mix.

4. RESULTS and DISCUSSION

Considering our baseline scenario, according to the existing vehicle and the primary considerations done at the inventory, without sharing vehicles, we estimated a total value of energy consumption per vehicle and kilometer of 0.361 [MJ/v-km]. In terms of GHG emissions of the Ghisallo vehicle, it is estimated to emit 29.033 [g CO_2 eq/v-km]. In either case, the production stage is responsible for the most significant impact share, with 50.68% and 42.11%, respectively. These numbers and the distribution of impact share by pillar for the baseline scenario are described in **FIGURE 6**.

FIGURE 6 - Baseline scenario - Percentage of impact by pillar given final values of a) Energy consumption and b) GHG emissions per vehicle-kilometer

Moreover, we analyzed the values by comparing the LCA results for the multiple alternative scenarios. By analyzing the first five alternative scenarios, it was possible to verify that alternative scenarios number 2 and 5 would not benefit the environmental impacts compared to the base scenario. Regarding energy consumption, their results were approximately 9% and 340% worst, respectively, while regarding GHG emissions, approximately 10% and 300% worst, respectively. Therefore, if the assumptions such as the transport of Ghisallo by plane or the possibility of operating a network of Ghisallos as shared mobility vehicles were applied in real life, these could induce worst LCA results. The contrary happened when assuming the replacement of the aluminum parts with steel, 100% renewable energy mix, or bike lanes 90% of the time. These scenarios (1,3 and 4) revealed that if these actions were taken in place, the results of LCA could be enhanced.

As a result, combining the changes applied at favorable alternative scenarios we analyzed the alternative scenario 6. It resulted in the estimation of a potential scenario where Ghisallo could consume 25% less energy and emit 45% fewer GHG emissions than if in the base scenario. Therefore, to change aluminum parts by steel, to use more bike lanes instead of typical 100% road use, and to increase the share of renewables in the energy mix to 100% resulted in final total values of 0.268 [MJ/v-km] and 15.850 [g CO_2 eq/v-km] at scenario 6. All these results can be confirmed by **FIGURE 7** and **FIGURE 8**.

FIGURE 7 - Energy consumption comparison between scenarios

FIGURE 8 - GHG emissions comparison between scenarios

Additionally, we performed a comparison between the results obtained for the base case scenario and the ones provided by ITF-Good to go excel tool for multiple mobility modes. When analyzing the values of Energy consumption and GHG emissions per vehicle-kilometer, it was possible to verify that the base values of 0.361 [MJ/v-km] and 29.033 [g CO_2 eq/v-km] for the Ghisallo vehicle are similar to values like mopeds, scooters, or bicycles. By analyzing both figures (**FIGURE *9*** and **FIGURE *10***), it was possible to verify that the Ghisallo's estimation of LCA results are in a range similar to multiple micromobility vehicles. Moreover, these types of vehicles are proved to be much more environmentally friendly than mobility modes like cars.

FIGURE 9 – Energy consumption per vehicle-kilometer - Comparison between Ghisallo (baseline scenario) and other vehicles

FIGURE 10 - GHG emissions per vehicle-kilometer - Comparison between Ghisallo (baseline scenario) and other vehicles

To complement our analysis, besides comparing the results between Ghisallo and other vehicles with the assistance of the used tool, in **TABLE *7*** we present a comparison between the results of this study and the results from literature for other micromobility vehicles. In particular we verify that Ghisallo estimated values of GHG emissions per vehicle-kilometer are in the range of values that peer authors have also estimated.

TABLE 7 – Comparison of LCA results between Ghisallo and other micromobility vehicles from the literature

Vehicle	Study	GHG Emissions (g CO_{2eq}/v-km)
Ghisallo	Present	29
E-scooter	(12)	165
E-moped	(43)	32
E-moped	(44)	59
E-moped	(45)	74
E-moped	(37)	20
Station-based Shared bike	(3)	65
Dock-less Shared bike	(3)	118

A limitation of our study was the lack of data related with the actual percentage of use on the path infrastructure. Further research should include sensitivity analysis to compare the impacts regarding different percentages of bike lane use versus road use. For that purpose, future work might benefit from increasing data availability provided by shared-mobility companies with GPS tracking. Moreover, since the assumptions in multiple scenarios are not supported by strong scientific facts, we believe a deeper sensitivity analysis could take place in the future. For instance, different configurations of bike lane and road lane could be assessed instead of just the two cases where we considered 0 or 90% bike lane usage. Likewise, different scenarios of renewable energy penetration will allow to understand what the environmental impacts of Ghisallo are when operating in cities with multiple characteristics.

Finally, Ghisallo should be study in terms of what could be its economic and social impacts. In particular, these LCA does not consider what is the exposure of the user to pollutants and noise. Likewise, our vehicle could be used like cargo bikes are to perform logistical operations. All of these potential applications could also be studied from a perspective of life cycle cost analysis to understand how lucrative this option from a business point of view could be.

5. CONCLUSIONS

This work assesses the life cycle of a novel micromobility device, the Ghisallo vehicle. 'ITF – Good to Go?' tool, was adapted for this purpose to include a new vehicle, previously not existent at the database of the tool, with a satisfactory degree of concordance between inputs from the GREET database and the energy source coming from European and Portuguese electricity grids. However, the GREET database should be adapted in future studies with European-based data to improve the accuracy of the results. Moreover, a new LCA should be performed once the vehicle reaches a "design freeze" stage, which means no more parts will be changing at the design stage. Once that stage is completed, even the manufacturer companies should be consulted to enhance inventory accuracy, mainly regarding the percentages of recycled materials used at production stages, such as aluminum and steel. The plane used to transport the vehicle to Portuguese islands instead of distributing it in continental territory showed a potential to be 10% more harmful to the environment. Also, the estimation of 0 or 90% usage of bike lanes should be reevaluated in further studies according to accurate data.

In any case, the results show a preliminary estimation of the potential of the Ghisallo vehicle to be included in the market as a similar alternative to e-scooters, e-bikes, and conventional bicycles. From the current state of development of our vehicle's LCA, we could also confirm that the substitution of aluminum materials for steel and the significant participation of renewable sources on the electricity grid will benefit any LCA results for this type of vehicle. Moreover, the results allowed us to conclude that shared micromobility has a significant impact on the results, mainly due to the decrease of the vehicles' lifetime and the extra need for operational services. Perhaps in future studies, both transport and operational services pillars could evaluate the impacts of using electric vans to do those tasks instead of diesel vehicles. Globally, the alternative scenario 6 with multiple improvements allows identifying a potential to reduce the life cycle impact of Ghisallo by 25% on energy consumption and 45% on GHG emissions.

Thus, this study reveals the preliminary results of a LCA to the Ghisallo vehicle which are concluded to be in line with strategic plans for developing new mobility solutions. Those are expected to be sustainable from the cradle to the grave in multiple economic, social, environmental, and operational sectors. The limitations of this study were due to the use of a non-European database (GREET) and raw estimates assumed at the pillars of transport, infrastructure, and operational services. Therefore, as soon as the manufacturers fix the bill of materials and the characteristics of device operability are more precise, namely the percentage of bike lane usage and the mileage between production and sales site, more relevant will be the contributes of further LCA studies, in particular by contributing to improve the accuracy of results and confirming the identified potential while addressing the identified limitations.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: J. Calão, A.G. Completo, M.C. Coelho; data collection: J. Calão, A.G. Completo; analysis and interpretation of results: J. Calão, A.G. Completo, M.C. Coelho; draft manuscript preparation: J. Calão and D.L. Marques. All authors reviewed the results and approved the final version of the manuscript.

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